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External Tank Bipod Fitting Bolted Attachment Locking Insert Performance

June 22, 2006


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Volume I: Technical Position Paper

1.0 Signature Page

Technical Team Members


Dr. Curtis Larsen, NESC Lead

Dr. Kenny Elliott, LaRC

John McManamen, JSC


Dr. Ivatury Raju, LaRC

Tim Wilson, LaRC

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2.0 Team Member List

Dr. Curtis Larsen, NESC	NESC Discipline Expert (NDE), Mechanical Analysis, Team Lead
Dr. Kenny Elliott, LaRC	Structures
John McManamen, JSC	NDE, Mechanical Systems
Dr. Ivatury Raju, LaRC	NDE, Structures
Tim Wilson, LaRC	NESC Deputy Director

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3.0 Executive Summary

Following STS-107, the External Tank (ET) Project implemented corrective actions and configuration changes at the ET bipod fitting. Among the corrective actions, the existing bolt lock wire which provided resistance to potential bolt rotation was removed. The lock wire removal was because of concerns with creating voids during foam application and potential for lock wire to become debris. The bolts had been previously lubricated to facilitate assembly but, because of elimination of the lock wire, the ET Project wanted to enable the locking feature of the insert. Thus, the lubrication was removed from bolt threads and instead applied to the washer under the bolt head. Lubrication is necessary to maximize joint pre-load while remaining within the bolt torque specification. The locking feature is implemented by thread crimping in at four places in the insert. As the bolt is torqued into the insert the bolt threads its way past the crimped parts of the insert. This provides the locking of the bolt, as torque is required to loosen the joint after clamping. Refer to Figures 3.0-1 and 3.0-2.

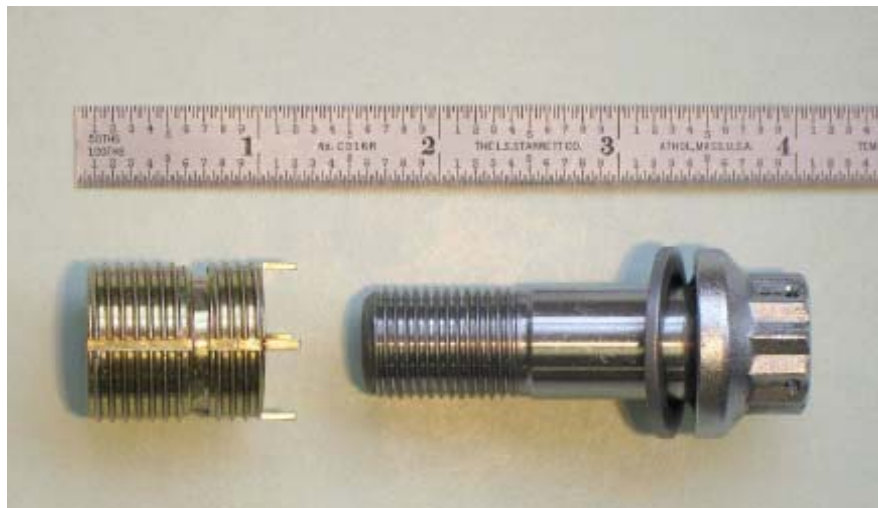



Figure 3.0-1. Insert and Bolt Used in the Design
[ref. Wingate, ET Bipod Fitting Bolted Joint Attachment Design and Locking Insert Performance presentation, June 13, 2006]

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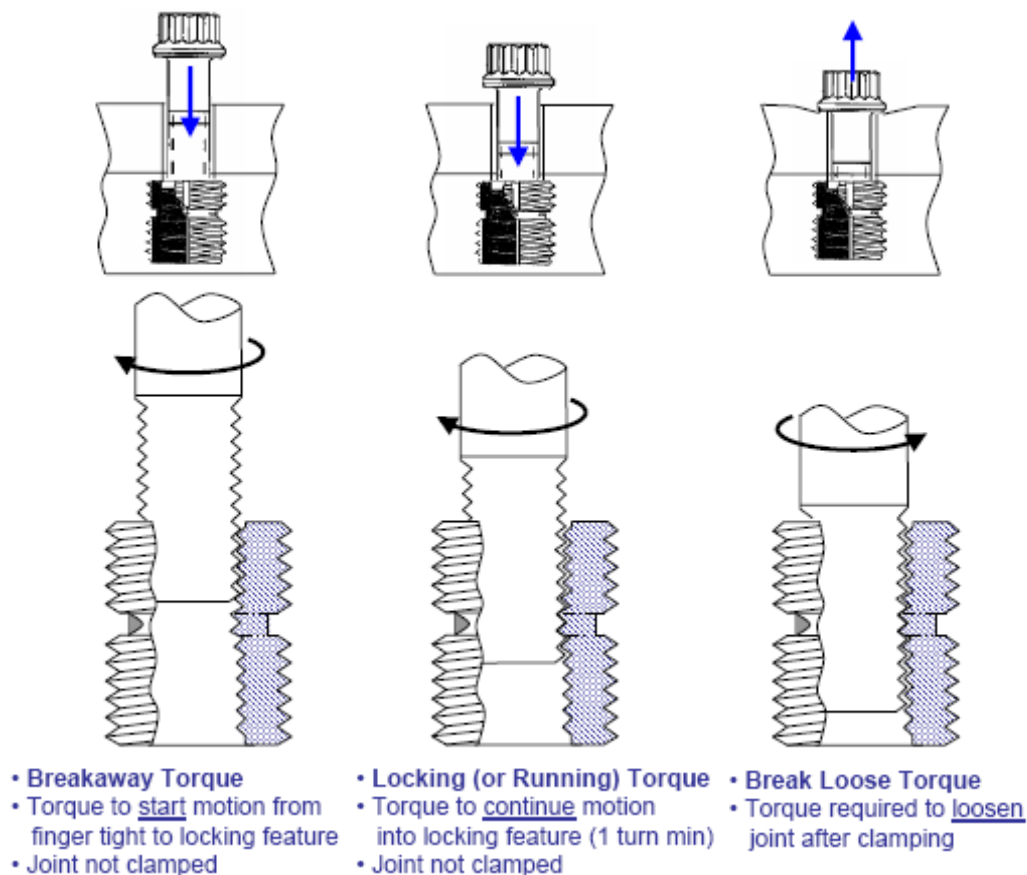


Figure 3.0-2. Insert Locking Feature
[ref. Wingate, ET Bipod Fitting Bolted Joint Attachment Design and Locking Insert Performance presentation, June 6, 2006]

Following the foam loss near the bipod on STS-114, the ET Project implemented corrective actions to seal any potential leak paths along the bipod heater wiring. This required disassembly of ET-119 and ET-120. During disassembly of the bipod fittings, the running torque of the attachment bolts was monitored and found to be *below* the specification minimum required to ensure the integrity of the locking insert to resist bolt rotation as shown in Table 3.0-1.


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Table 3.0-1. Measured running torque in the attachment bolts in ET-119 and 120

Minimum required running torque is 32 in-lbs.

ET-119 Starboard fitting:	4 of 6 inserts failed @ 0-15 in-lbs.
ET-119 Port fitting:	6 of 6 inserts failed @ 5-15 in-lbs.
ET-120 Starboard fitting:	6 of 6 inserts failed @ 0-27.5 in-lbs.
ET-120 Port fitting:	5 of 6 inserts failed @ 17.5-25 in-lbs.

As the table shows, this raised concerns that, after the joint had been preloaded, the secondary locking feature of the insert was no longer effective to prevent vibration loosening of the fasteners. The ET Project studied the bolt and insert design to determine causes and corrective actions. The ET Project confirmed through torque/tension testing with minimum and maximum thread engagement that lower values of thread engagement degrades the locking feature. The bolts were lengthened by 1/8-inch to provide more thread engagement (~2 additional threads) but the effectiveness of this change has not been verified.


Bolted Joint Systems

Engineering standards for reliable, safe bolted fastening systems exposed to fluctuating loads require both adequate bolt torque to provide joint preload and the provision of a secondary locking feature. This is done either by lock-wire or some other means of developing fastener running torque that will resist bolt rotation. Typically, this is attained through a threaded insert or nut with a mechanical locking feature. Relative slip between joint surfaces and bolt bending are dominate conditions for vibration loosening. The bipod joint has two shear pins intended to eliminate slip and bolt bending.

Current Flight Rationale

The ET Project position is that the current joint design and installation torque levels provide protection against vibration loosening for the following reasons:

- Shear pins eliminate relative slip of joint surfaces
- High preload prevents joint separation (+0.03 margin on separation by analysis)
- Benign dynamic environment for loosening
- Longer bolts with increased thread engagement mitigate preload degradation of insert locking feature

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- Developmental testing at Marshall Space Flight Center (MSFC) confirms that preload mitigates vibration loosening
- Elimination of lube on bolt threads

Space Shuttle Program Response

Mr. Paul Shack, the Space Shuttle Program Lead Engineer, convened a meeting of the Shuttle Engineering Review Board (SERB) on June 13, 2006. The goal of the meeting was to disposition concerns with the bipod fitting and attachment system to determine if flight worthiness could be supported. The meeting agenda focused on two activities:

1. To hear all questions and concerns relative to the bipod fitting and attachment system from Johnson Space Center (JSC) Engineering, JSC Safety and Mission Assurance (S&MA), the NASA Engineering and Safety Center, MSFC Engineering, and MSFC S&MA. Specific concerns were presented by JSC Engineering and S&MA, and by the NESC. MSFC Engineering and S&MA noted that they were already convinced of the flightworthiness of the joint.
2. To examine all the pertinent technical analysis and test data available from the ET Project, MSFC Engineering, and Lockheed Martin. Data and rationale previously presented at the June 6, 2006, Loads Panel were reviewed and supplemented by new specimen test data and additional analyses.

The fundamental, common concern from JSC Engineering, S&MA, and the NESC was the lack of sufficient test data to demonstrate the locking inserts with the longer fasteners installed after STS-114 would be effective in providing the specified running torque after application and release of the joint preload. MSFC and Lockheed Martin directly addressed this concern by presenting the results of post-preload breakaway torque tests performed over the previous weekend on 16 joint stacks similar to those shown in Figure 4.2-1. The results of these tests are summarized in Figure 3.0-3 below from Mr. Rob Wingate's presentation.

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Bipod Fitting Inserts Locking Feature Issue

• Post Preload Breakaway Torque - Test Results

- Tested 16 individual joint stacks at ambient conditions
- Joint stack representative of max thickness components
- Torque applied consisted of measured running torque plus 190 ft-lbs
- Bolts tested included typical Bolt/Insert hardware utilized at this location

Breakaway torque in the loosening direction for the bipod fitting inserts (34L2-10L15), after torquing the bolt to 190 ft-lbs above the running torque.

ID		breakaway torque (in-lbs)					
		1st half turn		2nd half turn		3rd half turn	
		initiate movement	Max torque	initiate movement	Max torque	initiate movement	Max torque
PBF-1	PBF 26L2P10H16	115	127	117	135	117	127
PBF-2	PBF 26L2P10H16	35	57	48	55	50	60
PBF-3	PBF 26L2P10H16	35	52	47	55	42	55
PBF-4	PBF 26L2P10H16	42	50	37	65	55	60
PBF-5	PBF 26L2P10H16	30	55	55	57	56	57
PBF-6	PBF 26L2P10H16	55	65	60	77	55	55
PBF-7	PBF 26L2P10H16	25	35	30	45	35	40
PBF-8	PBF 26L2P10H16	20	35	25	35	23	35
PBF-9	PBF 26L3P10-16	45	67	60	72	60	70
PBF-10	PBF 26L3P10-16	17	32.5	20	27	25	27.5
PBF-11	PBF 26L3P10-16	24	40	27	45	35	55
PBF-12	PBF 26L3P10-16	15	40	27	36	32	36
PBF-13	PBF 26L3P10-16	35	100	65	90	55	57
PBF-14	PBF 26L3P10-16	25	32	25	30	27	35
PBF-15	PBF 26L3P10-16	82	115	92	115	90	100
PBF-16	PBF 26L2P10-16	37	57	32	55	35	45


These fasteners are the same types used on ET119

Figure 3.0-3. Bipod Fitting Insert Locking Feature Test Results
[ref. Wingate, Bipod Fitting Inserts Locking Feature Issue Additional Flight Rationale presentation, June 13, 2006]

The consensus of all parties at the SERB was that this data adequately demonstrated the capability of the locking insert, when used with the longer bolt, to provide the required torque for resisting bolt rotation. Additional mitigating data was provided addressing the magnitude of the random vibration environment at the bipod fitting, magnitude and number of cycles of the applied flight loads compared to the design loads, shear motion resistance of the fitting, margin of safety against joint separation, and additional resistance to bolt rotation provided by the BX-265 foam applied over the bolt heads.

Based on all the information presented, all parties at the SERB agreed to the flightworthiness of the current bipod fitting design to support the STS-121 and STS-115 missions. The open Program action was closed relative to the STS-121 mission. Mr. Shack advised anyone having any long term, lingering concerns that they should present those concerns to the Space Shuttle Program in the form of a white paper in a logical, well thought out fashion, including a clear process that would be acceptable for answering the concerns.

One formal action and several informal actions were assigned that are not flight constraints. The ET Project was formally asked to provide a further explanation for the derivation of the 30 percent preload loss estimate for the bipod joint, specifically concerning what appeared to be anomalous preload loss data reported for two bolts in the joint preload relaxation testing

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performed prior to STS-114. The ET Project agreed to an informal action to provide the details of the fitting bolt torque procedure and sequence to Mr. David Lowry of JSC Engineering. Further, the ET Project agreed to explore a recommendation from Mr. Lang, USA Chief Engineer, to provide adequate tools to measure and record the break loose torques on the fitting bolts during any future disassemblies. A request was also made to add a column to the table shown in Figure 3.0-3 to document the running torque measured during the bolt insertion and first engagement of the locking feature (subsequently provided by Mr. Wingate, refer to Appendix B).


From the NESC, several areas for further consideration or investigation were suggested to the ET Project. Mr. McManamen suggested that the potential exists for bending to be induced in the bolts from even the small lateral motion allowed by the clearance of the fitting shear pins. Bolt bending with alternating loads is a key factor in bolt loosening, as the contact loads between the treads fluctuate to react the bolt moment.

Mr. Elliott suggested that the low frequency loads environment may not be as benign as thought because vibration loosening is a displacement governed phenomena and the largest displacements may occur during the roll-out loads that had not been considered. However, the presence of the preload and the insert locking feature mitigate this risk. An additional observation was the presence of the foam applied over the bolt heads will resist bolt back out.

Mr. Elliott also asked if an alternate root cause of the bolt loosening was considered, that of the manufacturing process error or tooling difficulties to have reduced the running torque. Specifically, experience by others has shown that a slightly oversized drill bit or a worn tap can have detrimental effects to insert locking performance. A suggestion was that the ET Project verify the correct tooling is used in the fabrication and rework processes. A further recommendation was that the NESC consider a simple test to verify the thread engagement root cause. The test should isolate the factors of preload and thread engagement to demonstrate the variability of locking torque as a function of thread engagement and preloads.

Finally, Mr. Elliot commented that the standard design practice rule of thumb is to design the bolt and insert to allow 1 to 1.5 bolt diameters of insert engagement. He suggested that the NESC perform an independent check of the bolt/insert stress calculations to ensure adequate thread engagement.

In the closing remarks for MSFC Engineering, Mr. Wingate appealed to the Shuttle Program and the NESC to consider an effort to standardize the requirements and practices for the use of locking features for bolts and inserts in aerospace applications.

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4.0 Findings, Recommendations, and Observations

4.1 Findings


- F-1.** While the current design mitigates the potential for vibration loosening of the joint, it does not totally eliminate the possibility and significant uncertainty remains. The shear pins, for example, eliminate most of the relative slip in the joint, but due to inherent tolerances, some amount of movement remains. The high preload prevents joint separation and mitigates vibration loosening, but determination of actual preload in the present joint configuration is uncertain. Preload is not a function of increased thread engagement, and as such it cannot be considered as a mitigating feature. The dynamic environments, both those encountered during roll to the pad and in flight, have not been assessed or quantified to establish the level that will or will not induce vibration loosening.

NESC maintains the level of uncertainty is high enough to warrant additional testing to verify integrity of the ET bipod fastening system, especially in light of recent experience which indicates the inserts' secondary locking feature may not be adequate to prevent bolt rotation should dynamic loads act to loosen the fasteners.

4.2 Recommendations

- R-1.** Because the bipod fitting is the primary load path between the Orbiter and the ET, the NESC recommends test verification of the fastening performance of this bolted joint sufficient to demonstrate integrity of the secondary locking feature or to verify the joint is not susceptible to dynamic loosening. Two verification test options are proposed. Successful completion of the first will demonstrate integrity of the secondary locking feature and, if successful, is adequate for flight. If unsuccessful the second is required to demonstrate flight loads will not loosen the joint.

1. Component test: Demonstration at the fastener/insert level that the specification minimum running torque (32 in-lbs) is provided after application and removal of preload. The test specimens should consist of a sandwich of the aluminum, phenolic, copper, and titanium materials of the actual joint. Refer to Figure 4-1.1. Load application should be representative of the bolt preload applied for flight with adequate time allowed after torque application and prior to measurement of running torque (1-2 hours) to allow for any relaxation of preload.
2. System test: Demonstration of no fastener rotation (loosening) with flight configuration hardware under fluctuating flight loads to four times (4 x) the mission exposure. The test setup should duplicate the flight configuration and should

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incorporate the following: (1) Cryogenic temperature on the 1.25 in. aluminum 2219 LH2 tank wall, (2) heating of the phenolic, and (3) load environment applied to the joint. Test configurations with BX-265 foam closeouts after installation are desirable.



Figure 4.2-1. Example Component Test Specimens
[ref. Wingate, ET Bipod Fitting Bolted Joint Attachment Design and Locking Insert Performance presentation, June 13, 2006]


4.3 Observations

There were no significant observations.

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5.0 References

1. Wingate, Rob. "ET Bipod Fitting Bolted Joint Attachment Design and Locking Insert Performance", June 6, 2006. Presented to the SSP Loads and Dynamics Panel.
[http://sspweb.jsc.nasa.gov/webdata/lsdp/lp_2006/060606/01\)%20ET_Bipod_Inserts_06Jun06.pdf](http://sspweb.jsc.nasa.gov/webdata/lsdp/lp_2006/060606/01)%20ET_Bipod_Inserts_06Jun06.pdf)
2. Wingate, Rob. "ET Bipod Fitting Bolted Joint Attachment Design and Locking Insert Performance", June 13, 2006. Presented to the SSP Shuttle Engineering Review Board.
http://sspweb.jsc.nasa.gov/webdata/mss/SERB/06132006SSERB_01E_ET_Bipod_Inserts_RWingate.pdf
3. Wingate, Rob. "Bipod Fitting Inserts Locking Feature Issue Additional Flight Rationale", June 13, 2006. Presented to the SSP Shuttle Engineering Review Board.
http://sspweb.jsc.nasa.gov/webdata/mss/SERB/06132006SSERB_01E_BackUp_AddlRationale2_RWingate.pdf
4. Wingate, Rob. Bipod Follow-Up, electronic file via email transaction to Curtis Larsen, Appendix B, June 20, 2006.


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Appendix A. ITA/I Request Form (NESC-PR-003-FM-01)

NASA Engineering and Safety Center Request Form		
Submit this ITA/I Request, with associated artifacts attached, to: nrbexecsec@nasa.gov , or to NRB Executive Secretary, M/S 105, NASA Langley Research Center, Hampton, VA 23681		
Section 1: NESC Review Board (NRB) Executive Secretary Record of Receipt		
Received (mm/dd/yyyy h:mm am/pm) 6/9/2006 12:00 AM	Status: New	Reference #: 06-032-E Rev 1
Initiator Name: Rod Wallace	E-mail: rodney.o.wallace@nasa.gov	Center: JSC
Phone: (281)-483-3904, Ext	Mail Stop: MS	
Short Title: ET Bipod Bolt Locking Feature Verification Description: On June 6, 2006, Dr. Curtis Larsen, NDE for Mechanical Analysis, received an e-mail and telephone request from Mr. Jene Richart and Mr. Rod Wallace of the Space Shuttle Systems Engineering and Integration Office to support a special meeting of the Shuttle Loads and Structural Dynamics Panel on concerns from JSC Engineering for potential joint gapping in the interface struts and fittings between the External Tank (ET) and the Orbiter and Solid Rocket Booster (SRB). The effect of such gapping on the local interface stiffnesses, and subsequent potential for inaccuracies in the Shuttle Vehicle dynamic models and flight load predictions was the main focus of the JSC concerns. Dr. Larsen contacted Dr. Ivatury Raju, NDE for Structures, and Mr. John McManamen, NDE for Mechanical Systems, to join him in attending the Loads Panel. The Loads Panel convened at 2:30 pm that day with Mr. McManamen and Drs. Raju and Larsen participating by telecon and WebEx. MSFC Engineering and Lockheed Martin presented analyses and test data to attempt to address JSC's concerns.		
Source (e.g. email, phone call, posted on web): Email		
Type of Request: Assessment		
Proposed Need Date:		
Date forwarded to Systems Engineering Office (SEO): (mm/dd/yyyy h:mm am/pm):		
Section 2: Systems Engineering Office Screening		
Section 2.1 Potential ITA/I Identification		
Received by SEO: (mm/dd/yyyy h:mm am/pm): 6/9/2006 12:00 AM		
Potential ITA/I candidate? <input type="checkbox"/> Yes <input type="checkbox"/> No		
Assigned Initial Evaluator (IE): Curtis Larsen		
Date assigned (mm/dd/yyyy): 6/9/2006		
Due date for ITA/I Screening (mm/dd/yyyy):		
Section 2.2 Non-ITA/I Action		
Requires additional NESC action (non-ITA/I)? <input type="checkbox"/> Yes <input type="checkbox"/> No		
If yes:		
Description of action:		
Actionee:		
Is follow-up required? <input type="checkbox"/> Yes <input type="checkbox"/> No If yes: Due Date:		
Follow-up status/date:		
If no:		
NESC Director Concurrence (signature):		

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Request closure date:		
Section 3: Initial Evaluation		
Received by IE: (mm/dd/yyyy h:mm am/pm):		
Screening complete date:		
Valid ITA/I candidate? <input type="checkbox"/> Yes <input type="checkbox"/> No		
Initial Evaluation Report #: NESC-PN-		
Target NRB Review Date:		
Section 4: NRB Review and Disposition of NCE Response Report		
ITA/I Approved: <input checked="" type="checkbox"/> Yes <input type="checkbox"/> No	Date Approved: 6/8/2006	Priority: - Select -
ITA/I Lead: Curtis Larsen, Phone () - , x		
Section 5: ITA/I Lead Planning, Conduct, and Reporting		
Plan Development Start Date:		
ITA/I Plan # NESC-PL-		
Plan Approval Date:		
ITA/I Start Date	Planned:	Actual:
ITA/I Completed Date:		
ITA/I Final Report #: NESC-PN-		
ITA/I Briefing Package #: NESC-PN-		
Follow-up Required? <input type="checkbox"/> Yes <input type="checkbox"/> No		
Section 6: Follow-up		
Date Findings Briefed to Customer:		
Follow-up Accepted: <input type="checkbox"/> Yes <input type="checkbox"/> No		
Follow-up Completed Date:		
Follow-up Report #: NESC-RP-		
Section 7: Disposition and Notification		
Notification type: - Select -		Details:
Date of Notification:		
Final Disposition: - Select -		
Rationale for Disposition:		
Close Out Review Date:		

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Form Approval and Document Revision History

Approved: _____ <div style="text-align: center;">NESC Director</div>	_____ <div style="text-align: center;">Date</div>
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Version	Description of Revision	Office of Primary Responsibility	Effective Date
1.0	Initial Release	Principal Engineers Office	29 Jan 04



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Appendix B. Bipod Breakaway Torque

External Tank PRELIMINARY

Bipod fitting insert breakaway and running torque results tested on 6/11/06-6/12/06.


Prior to installation STP2014 has a minimum breakaway torque requirement of 32 in-lbs and maximum running torque requirement of 300 in-lbs. Running torque before seating the bolt measured during 4 to 6 turns past the locking feature.

ID	Bolt	Running Torque (tightening direction) before installing bolt (in-lbs)	breakaway torque (in-lbs) (loosening direction) after torquing the bolt to 190 ft-lbs + the running torque					
			1st half turn		2nd half turn		3rd half turn	
			initiate movement	Max torque	initiate movement	Max torque	initiate movement	Max torque
Prerun -1	PBF 26L2P10-16	144	45	67	60	72	60	70
Prerun -2	PBF 26L2P10-16	108	17	32.5	20	27	25	27.5
1	PBF 26L2P10H16	264	115	127	117	135	117	127
2	PBF 26L2P10H16	150	35	57	48	55	50	60
3	PBF 26L2P10H16	84	35	52	47	55	42	55
4	PBF 26L2P10H16	192	42	50	37	65	55	60
5	PBF 26L2P10H16	156	30	55	55	57	56	57
6	PBF 26L2P10H16	108	55	65	60	77	55	55
7	PBF 26L2P10H16	96	25	35	30	45	35	40
8	PBF 26L2P10H16	84	20	35	25	35	23	35
9	VT 26L2P10H16	120	10	17	7	16	15	15
10	VT 26L2P10H16	138	30	47	40	55	45	52
11	VT 26L2P10H16	252	115	120	100	117	100	102
12	VT 26L2P10H16	96	10	35	37	40	25	35
13	PBF 26L2P10-16	324	bolt failed 300 in-lb max running torque requirement					
14	PBF 26L2P10-16	348	bolt failed 300 in-lb max running torque requirement, tested in the same insert as #13, discarded insert					
15	PBF 26L2P10-16	96	24	40	27	45	35	55
16	PBF 26L2P10-16	132	15	40	27	36	32	36
17	PBF 26L2P10-16	138	35	100	65	90	55	57
18	PBF 26L2P10-16	312	bolt failed 300 in-lbs max running torque requirement, tried working insert with same bolt, torque increased, discarded insert					
19	PBF 26L2P10-16	120	25	32	25	30	27	35
20	PBF 26L2P10-16	186	82	115	92	115	90	100
21	PBF 26L2P10-16	156	37	57	32	55	35	45
22	VT 26L2P10H16	264	120	145	125	145	130	148
23	VT 26L2P10H16	198	25	60	60	75	62	75
24	VT 26L2P10H16	120	20	27	17	30	25	35
25	VT 26L2P10H16	276	90	120	90	107	95	110
26	VT 26L2P10H16	240	37	77	65	90	72	87
27	VT 26L2P10H16	276	125	125	97	115	98	112
28	VT 26L2P10H16	72	10	20	15	22	17	24
29	VT 26L2P10H16	204	75	80	60	100	95	112
30	VT 26L2P10H16	60	5	10	2	10	5	12
31	PBF 26L2P10-16	60	30	40	18	20	20	20
32	VT 26L2P10H16	288	90	137	115	138	140	147
33	VT 26L2P10H16	108	5	10	5	10	7	15

VT fasteners not used for bipod fitting installation on ET-119 or ET-118.

PBF = PB Fasteners, Gardena, CA

VT = Valley-Todeco, Sylmar, CA

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Approval and Document Revision History

Approved: _____	Original signed on file _____ NESC Director	6/28/06 _____ Date
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Version	Description of Revision	Office of Primary Responsibility	Effective Date
1.0	Initial Release	NESC Chief Engineer's Office	